STUDYING SOLUTE AND PARTICULATE SEDIMENT TRANSFER IN A SMALL MEDITERRANEAN MOUNTAINOUS CATCHMENT SUBJECT TO LAND ABANDONMENT

P. LLORENS*, I. QUERALT, F. PLANA AND F. GALLART

Institute of Earth Sciences, Jaume Almera (CSIC). Solé i Sabarís s/n, 08028-Barcelona, Spain

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ABSTRACT

The sediment budget of the small research catchment of Cal Parisa (Vallcebre, Eastern Pyrenees) was studied by hydrological monitoring and assessment of the erosion rates in the major sediment sources. This area is characterized by clayey mudrock prone to landsliding and badland erosion, but the catchment was selected in an area free of major badland features, as a representative of middle mountain regions where a system of terraces and drainage ditches had been built for agricultural use but is now abandoned. Streamwater chemistry is dominated by Ca^{2+} and HCO_3^- at concentrations close to calcite saturation. Total dissolved solids show dilution during runoff peaks and positive hysteresis loops that support a slow contribution of subsurface water. Relative dissolved ion concentrations are different for each event analysed. Particulate sediment yield is very low and represents only about 1 per cent of gross erosion in the catchment. Mineralogical analysis of suspended sediments shows an enrichment in calcite because of precipitation. Chemical analysis of suspended sediments, using common one-litre water samples, shows higher contents of Ca, P and Mn in transported sediment than in sediment source areas, attributed to the precipitation of calcite, and enrichment in organic particulate matter during events respectively for the two first elements, whereas enrichment in Mn remains uncertain. Solid matter yield is therefore clearly dominated by dissolved transport as a result of both high calcium bicarbonate concentrations in runoff waters and strong suspended sediment conveyance discontinuities. Land conservation structures are very effective because they are in good condition whereas the soil is covered by dense permanent vegetation. Nevertheless, this state is unstable because the network of drainage ditches needs maintenance; its spontaneous breakdown after abandonment may result in the rearrangement of the elementary stream network and gullying of old fields in hollows. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

To understand and cope with the problem of land conservation not only is it necessary to know the sediments yielded from a catchment, but is is also indispensable to determine the characteristics and dynamics of source areas and the sediment transport mechanisms and pathways from these source areas to the outlet of the catchment (Bordas and Walling, 1988).

The small catchment of Cal Parisa was selected in 1988 as representative of old mountain farming areas, in order to study the hydrological and geomorphic behaviour and fate of these areas as a contribution to the analysis of hydrological consequences of environmental changes.

The major purpose of this study is to analyse the main aspects of the transfer of sediment within this environment, studied through field observations, hydrological monitoring and laboratory analyses, and to discuss the implications for geomorphological and land conservation.

* Correspondence to: P. Llorens
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THE STUDY AREA

The Cal Parisa catchment is located in the headwaters of the Llobregat river (Vallcebre, Eastern Pyrenees, Spain), a mountainous area prone to gully erosion and landsliding (Clotet *et al*., 1988; Balasch *et al*., 1992). It occupies an area of 36 ha between 1400 and 1700 m a.s.l. and takes the form of a southeast-facing slope. The area of the more man-modified subcatchment, which is the subject of this paper, is about 17 ha.

The climate is Mediterranean mountainous, with a mean annual precipitation of about 850 mm, subject to wide oscillations, and with a distinct dry season that appears from mid-June to mid-August, when intense rainstorms occur. Mean annual temperature is about 9°C.

The hillslope gradients range from 5 to over 70 per cent, but almost 60 per cent of the catchment shows gentle gradients from 10 to 30 per cent. The upper divide of the catchment is a cliff cut in limestone rocks.

Bedrock is mainly a smectite-rich mudstone of the non-marine upper Cretaceous Garumnian facies. These sediments have a silty granulometry due to the presence of abundant micrite and microsparite (about 62 per cent of $CaCO_3$), and the aggregates derived from the parent material show marked instability. This is in contrast to the high stability of the aggregates from soils developed on the same parent material (Solé *et al*., 1992).

The impact of past agricultural land use has promoted the present distinctive geoecological characteristics of the catchment. The terraced topography is drained by a network of man-made ditches, and has a vegetation cover of mesophile and xerophile grasslands with a spontaneous reafforestation of *Pinus sylvestris* on the areas abandoned in an early stage (Llorens, 1991; Llorens *et al*,. 1992).

Infiltration capacities are high because of the good structure of topsoils, and become enhanced during dry periods because of the role of deep desiccation cracks. Saturated hydraulic conductivities are very high in the shallow soil horizons and in the external rims of terraces (700 mm h^{-1}), but fall by several orders of magnitude in the deeper horizons and internal parts of terraces (Josa & Roda, 1994). Groundwater therefore moves very slowly, allowing the permanence of shallow aquitards and seasonal saturated areas.

Water erosion processes are controlled by a dense vegetation cover on about 98 per cent of the catchment area, with the exception of some small scattered bare areas with clayey bedrock outcrops (Llorens *et al*., 1992). The two main bare areas are scars of landslides that occurred in 1982 as a consequence of an extreme rainfall event (Gallart and Clotet, 1988).

MONITORING DESIGN AND METHODS

The instrumentation network of the more man-modified subcatchment, set up in 1989, consists of four rain recorders, a meteorological station and a hydrometric and sampling station based on a steel H flume with continuous recording of water stage, temperature (AD590) and conductivity (Crison), and provided with both automatic (ISCO) and stage samplers. These instruments are connected to several data-loggers (Unidata) that allow a 5 min step recording (Llorens and Gallart, 1992). Bedload was collected after the major events in the approach channel of the flume.

Hydrochemical analysis

This analytical method was used to characterize solid matter transport (Llorens, 1991). To measure total dissolved solids (TDS), continuous readings of electrical conductivity were translated, after calibration and correction for temperature, into TDS concentrations, using a relationship obtained in the laboratory through drying filtered samples of streamwater at moderate temperature (60°) in order to prevent the decomposition of $CaCO_3$.

Alkalinity was analysed shortly after sampling, and obtained by titration with HCl 0·02N, using the electrical conductivity of the sample as indicator; pH was measured at room temperature in the laboratory with a Crison pH meter.

Analysis of streamwater samples for major ions (Na^+, k^+, Ca^{2-} and Mg^{2-}, HCO_3^-, Cl, SO_4^{2-}, NO_2^- and NO_3^-), was carried out by means of atomic absorption spectroscopy (AAS) and liquid chromatography (LC).

Sedimentological, mineralogical and chemical analysis

Concentration of total suspended solids (TSS) of the streamwater samples was obtained by weighing filtered samples (0·45μm pore size).

Grain-size analysis of source materials and streamwater samples was obtained using a laser beam scattering analyser (Malvern).

Mineralogical analysis of source materials and filtered streamwater samples was performed through X-ray diffraction. The mineralogical characterization of streamwater samples was performed using a method adapted for membrane filters (Queralt *et al*., 1990) allowing the use of common one-litre water samples instead of large sampling volumes (Ongley *et al*., 1981).

Geochemical analysis of source materials and filtered streamwater samples was performed using X-ray fluorescence. The elements determined were Si, Al, Ti, Fe, Ca, Mg, Mn, Zn, K and P. The concentration of each element was calculated using the Ti content as a stable reference element (Thornton, 1983).

Gross erosion rates

Gross erosion rates in the two main erosion areas (landslide scars) were obtained through repeated topographic profiling during a 6·5-year period. Erosion rates from smaller patches were taken from data formerly obtained in similar areas in the Vallcebre catchment (Clotet *et al*., 1988). The role of mass movements was not quantitatively considered.

RESULTS AND DISCUSSION

During the period studied, from July 1989 to December 1990, nearly 90 per cent of the total runoff was produced during only six months (spring and autumn) and by only one event per month. This high runoff generation variability is explained by two main factors: the corresponding rainfall variability, and also the importance of antecedent soil moisture conditions, which disabled runoff at the basin outlet during summer in spite of the occurrence of rainstorms of up to 60 mm in one hour (Llorens, 1991).

Hydrological data interpretation and field observations indicated that runoff is generated by saturation of internal parts of farming terraces well connected to the drainage network, whereas Hortonian overland flow active on degraded areas does not reach the main drainage network (Llorens *et al*., 1992). The spatial distribution of saturated areas compared with the general topographic structure of the basin suggested that terraces modified the hydrological behaviour of the basin, increasing the peakedness of runoff events (Gallart *et al*., 1994).

Dissolved solids

Continuous dissolved solids concentration allowed the study of hysteresis behaviour, which shows dilution during runoff events, and nearly straight trends or clockwise hysteresis loops (Figure 1). This behaviour is commonly attributed to the immediate dissolution of mineral matter by rainfall or runoff waters, or to the very slow response of the underground water (Gregory and Walling, 1973). The latter hypothesis is coherent with the low hydraulic conductivities of deep soil horizons, whereas the moderate dilution of the first peak on Figure 1 suggests immediate dissolution, which becomes less important for subsequent peaks. Similar high concentrations of dissolved solids after dry periods have been observed in ephemeral Mediterranean streams (Piñol *et al*., 1992).

The chemical analysis of runoff samples taken during five events shows that the Cal Parisa streamwaters are highly mineralized, especially in calcium bicarbonate at concentrations close to saturation, with a high pH, moderate concentration of sulphate and low concentrations of magnesium, sodium, potassium and chloride (Table I).

There was a significant negative correlation between discharge and sulphate, magnesium, calcium, sodium and bicarbonate (classified from major to minor absolute correlation), whereas correlation is not significant with chloride (negative) or potassium (positive) (Table II).

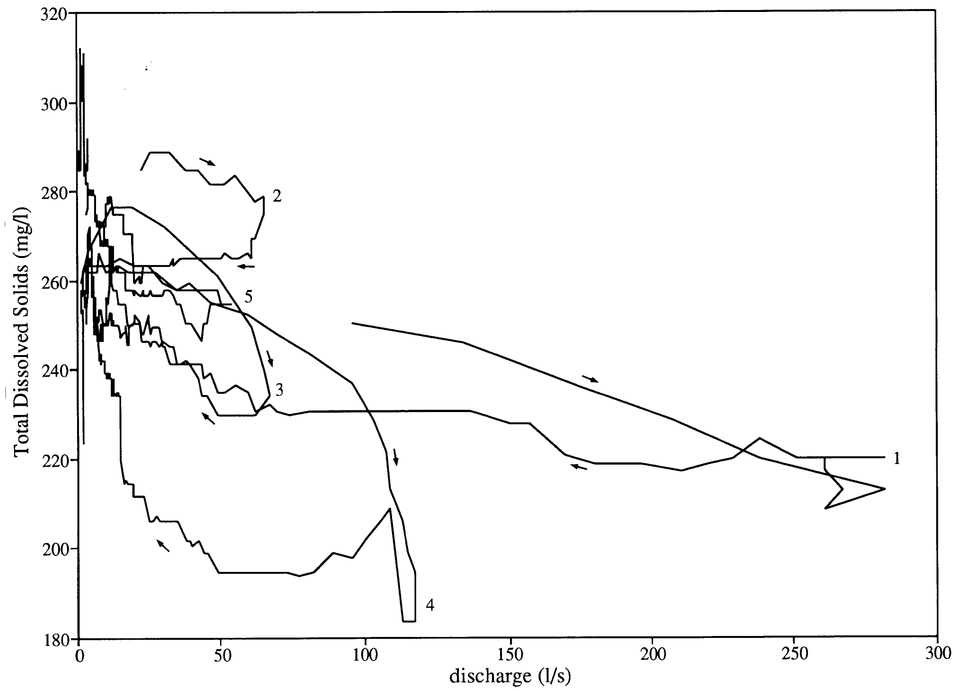

Figure 1. Hysteresis plot of total dissolved solids obtained from continuous electrical conductivity readings for a composite event (five peaks in six days) in May 1990. Numbers represent the order of runoff peaks

Table I. Main hydrochemical characteristics of streamwater samples

	pH	$[Na^+]$	$[K^+]$	$[Ca^{2+}]$	$[Mg^{2+}]$	$[HCO_3^-]$	$[Cl^-]$	$[SO_4^{2-}]$
n	33	65	64	67	67	56	63	66
Mean	7·90	0·12	0·03	3·84	0·15	2·87	0·03	0·58
CV	17·5	46·9	42·2	22·6	27·4	21·5	151·7	27·5

n = number of samples; mean concentrations (meq l^{-1}); CV = coefficient of variation (%)

Table II. Matrix of correlation coefficients among the dissolved ion concentrations from streamwater samples and the stream discharges. **Bold:** significant at the 5 per cent level; **<u>bold underlined:</u>** significant at the 1 per cent level

	Na^+	K^+	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	SO_4^{2-}
K^+	0·12						
Ca^{2+}	0·24	−0·23					
Mg^{2+}	**<u>0·45</u>**	0·16	**<u>0·81</u>**				
HCO_3^-	**<u>0·40</u>**	**−0·31**	**0·30**	0·11			
Cl^-	0·07	−0·16	−0·10	−0·22	0·10		
SO_4^{2-}	0·24	0·09	**<u>0·68</u>**	**<u>0·80</u>**	0·02	0·19	
Q	**−0·35**	0·12	**<u>−0·46</u>**	**<u>−0·50</u>**	**−0·29**	−0·11	**<u>−0·58</u>**

Two main groups of samples can be described.

1. Diluted samples from the rising limb and the peak of the hydrograph: these are waters with low mineralization, relatively rich in ions from vegetation leaching or from shallow soil horizons and with low contribution of subsurface water.
2. Concentrated samples from the ‘falling’ limb or the recession of the hydrograph: these waters show higher mineralization and contain ions from the deeper soils or direct contribution from subsurface waters.

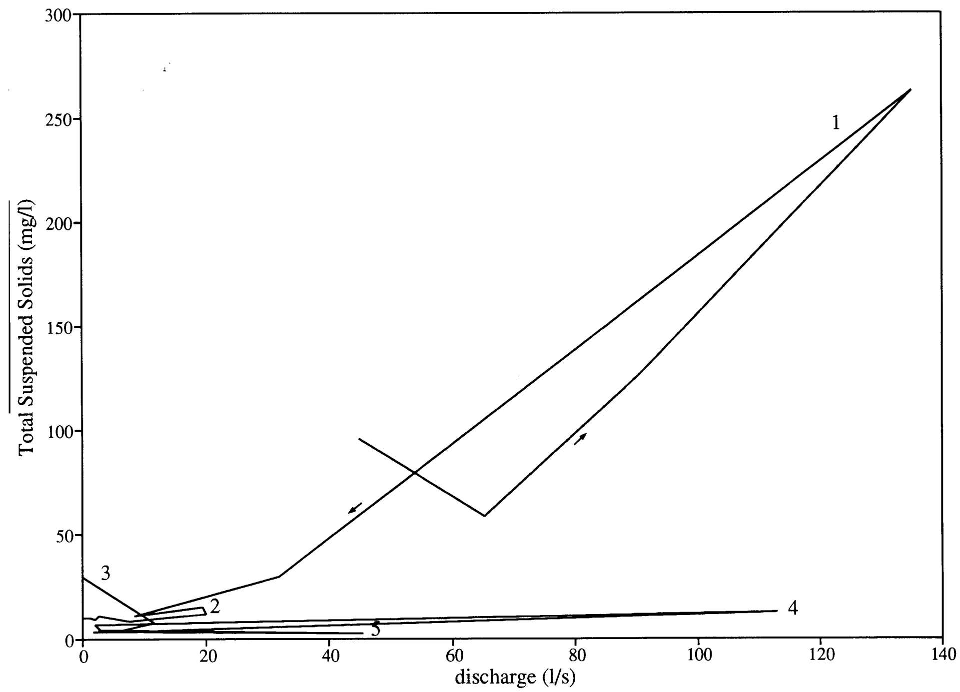

Figure 2. Hysteresis plot of total suspended-solids samples from the same event shown in Figure 1. Numbers represent the order of peaks

Important differences in relative concentrations of ions between the different events have been found.

Suspended sediment

Study of the suspended sediments, based on discrete samples, shows poor correlation between sediment concentration and discharge, and no clear hysteresis loops. Only the event in May 1990 (Figure 2) shows a clear shape, with a positive correlation between sediment concentration and discharge for the first peak, which reaches the highest concentration measured at the station; this seems to be the result of the scouring of the sediments accumulated in the stream channels during winter, which became exhausted for the subsequent peaks.

Mineralogy. The mineralogical characterization was performed with 35 suspended-sediment samples from the events studied, compared with 40 samples representative of materials from sediment source areas (Table III). The mineralogical determination included quartz, illite, smectite, kaolinite, calcite, feldspars and gypsum.

Table III. Relative concentrations of minerals in suspended-sediment samples from streamwaters and in samples taken from the presumed sediment source areas.

	Quartz	Illite	Smectite	Kaolinite	Feldspars	Calcite	Gypsum
Streamwaters							
n = 35							
Mean	10·1	14·5	4·3	14·7	0·8	54·9	0·6
CV	70·7	114·9	156·2	115·4	345·9	55·6	342·6
Sediment sources							
n =40							
Mean	9·9	10·5	28·2	21·3	0·0	30·0	0·0
CV	157·3	48·6	69·1	46·1	–	69·8	–

n = number of samples; mean concentrations (%); CV = coefficient of variation (%)

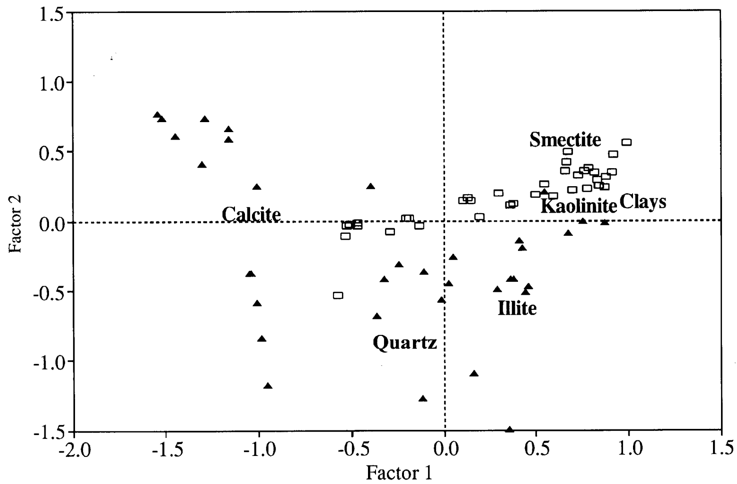

Figure 3. Mineralogical characteristics of suspended-sediment samples in streamwaters (▲) and of materials taken from the presumed sediment source areas (❑), on the plane defined by the two first factors of a principal component analysis (see text)

The only mineral present in all the samples is calcite, which is also the dominant mineral (41 per cent of the total content) together with the minerals of the clay group (49 per cent of the total content). Samples have low quartz content and very low feldspars and gypsum content (these last two minerals are not included in the subsequent examinations).

Owing to the high Ca^{2+} concentrations, clays are transported in flocculated conditions, demonstrated by the fact that the fraction smaller than 2 μm is always lower than 5 per cent in the grain-size analyses performed with untreated streamwater samples (not filtered, nor treated with sodic hexametaphosphate).

Figure 3 presents the distribution of the samples in the plane defined by the first two axes of a multivariate analysis (principal component analysis (PCA)) performed with the mineral contents. The first axis, which explains 52 per cent of the correlation, shows the opposition between calcite and clays, and seems to represent the enrichment in calcite produced by precipitation in the stream or immediately after when the sample is taken. This precipitation was commonly observed both in the streambeds and in the sampling bottles.

In this graph, samples from source areas are located in a sector with high clay content and low calcite content, whereas the samples from streamwater are distributed all along this main axis, representing different degrees of calcite enrichment.

The second axis, which explains 24 per cent of the correlation, shows the opposition between clay and quartz contents. This axis may represent a grain-size differentiation due to the sediment dynamics, as suggested by the negative correlation between quartz and smectite (significant at 1 per cent level) that represent respectively the largest and the smallest sediment particles. This dynamic differentiation is also coherent with the fact that sediment transport samples had higher variability in quartz content than source-area samples.

Table IV. Concentrations relative to Ti of elements in suspended-sediment samples from streamwaters and in samples taken from the presumed sediment source areas.

	Fe	Mn	Ca	K	Al	P	Si	Mg
Streamwaters								
$n = 25$								
Mean	23·2	2·0	848·7	24·9	100·1	14·2	97·0	1·6
CV	25·4	27·8	145·3	14·9	37·4	61·5	34·0	31·1
Sediment sources								
$n = 38$								
Mean	34·5	1·1	295·3	42·0	134·7	2·3	100·3	1·7
CV	19·1	45·7	76·3	14·7	59·9	32·1	42·2	22·4

n = number of samples; mean concentrations (% with respect to Ti); CV = coefficient of variation (%)

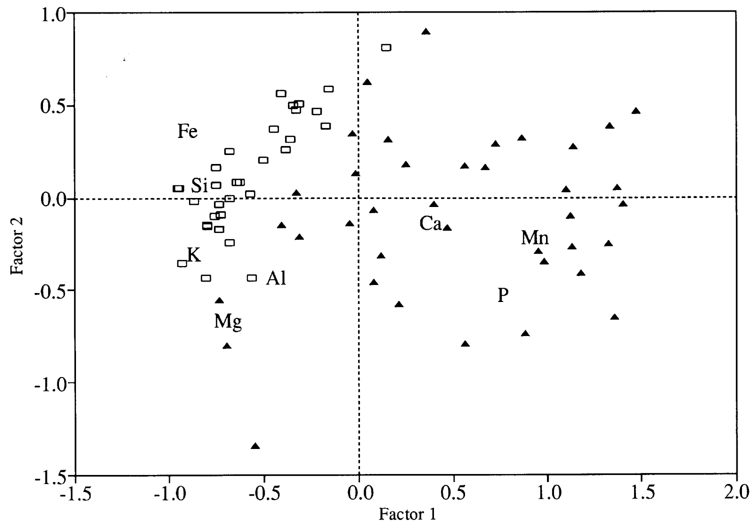

Figure 4. Chemical characteristics of suspended-sediment samples in the streamwaters (▲) and of materials taken from the presumed sediment source areas (❑), on the plane defined by the two first factors of a principal component analysis (see text)

Geochemistry. The chemical characterization was performed on the sediments filtered from 25 streamwater sample events and 38 samples from sediment source areas. The most abundant element in all the samples analysed is calcium, and then aluminium and silicon, the remaining elements having lower percentages (Table IV).

Figure 4 presents the distribution of the samples and variables on the plane defined by the first two axes of a multivariate analysis (PCA) performed with the relative concentrations of the elements analysed. The first axis, which explains 54 per cent of the correlation, opposes the main elements of clays (Si and Al), which are well correlated with Fe, K and Mg, versus P and Mn, which are negatively correlated with the former. The location of the streamwater samples on this graph demonstrates that they bear higher contents in P, Mn and Ca than the samples from source areas. The higher content in Ca can be attributed to calcite precipitation, as discussed before, whereas the higher contents of P and Mn have been attributed to enrichment of suspended sediment in organic matter and finer sediments respectively (Peart and Walling, 1986). Relative contents in P decrease with increasing TSS, which is compatible with a mainly organic origin (Probst, 1985). On the other hand, relative contents in Mn decrease somewhat with increasing TSS whereas the clay content is rather uniform; the enrichment of suspended sediment in Mn by selective erosion of fines is therefore rather unclear in this environment dominated by clays.

The second axis, which explains only 14 per cent of the correlation, is more difficult to explain, but as it plays a major role in source-area samples, it could represent some lithologic differentiation between smectite-rich clays and iron oxide-rich ones.

Samples from source areas are concentrated mainly around clay and Fe components whereas samples from streamwaters are distributed all along the first axis.

Sediment budget

The analysis of the sediment transport characteristics of the events (Llorens, 1991), on the basis of 67 streamwater samples, shows that there are high and sustained concentrations of dissolved solids, mean concentration is about 269 mg l^{-1} with a coefficient of variation of about 2 per cent, and low and very variable concentrations of suspended solids; mean concentration is about 25 mg l^{-1} with a coefficient of variation of about 123 per cent.

These characteristics indicate that the pattern of solid export is clearly dominated by dissolved solids transport (TDS), about four times greater than the suspended solids transport (TSS), and about 100 times greater

than bedload transport. These figures represent a total annual exportation of mineral matter of about 0·19 tm ha^{-1} a^{-1}, the contribution of dissolved and suspended solids being 0·15 and 0·04 tm ha^{-1} a^{-1} respectively.

The assessment of gross erosion rates in the main sediment sources within the catchment gave 33 mm a^{-1} for the two mudflow scars and 9 mm a^{-1} for the smaller scattered bare areas. These rates represent about 60 tm a^{-1} of gross erosion from these areas, and 3.5 tm ha^{-1} a^{-1} if averaged for the whole basin (Llorens and Gallart, 1991; Llorens *et al*., 1992).

The comparison of volumes shows therefore that exported particulate sediments represent only 1 per cent of the gross erosion. Field evidence and the results of geochemical analyses of sediments suggest that these assumed sediment sources do not contribute to the sediment export, because they are disconnected from the drainage network. Indeed, sediment eroded from bare areas becomes deposited a short distance away when the flow spreads onto well-vegetated old terraces. The exported sediment comes from the drainage net itself, together with some organic matter-rich sediments coming from topsoils elsewhere.

In the long term, erosion without sediment exportation represents a change in landforms, which become unstable. Geomorphic processes active on the steep hillslope below the limestone cliff (creeping, occasional mudflows and active erosion in their scars) induce rock falls from the limestone cliff, but also increase the thickness of deposits at the foot, which may be subject to mass movement.

On the other hand, the lack of maintenance of the terrace and ditch system is beginning to have some geomorphic and hydrological consequences. Failures of terrace banks are scarce and do not seem to be a significant degradation hazard because vegetation grows easily in the topsoil at the terrace edges. Water overflowing from ditches produces localized erosion in terrace banks of concave areas and is perceived as a major mid-term erosion hazard because the network is unstable and the natural drainage pathways are occupied by terraced fields. The degradation of the man-made ditches results in the saturation and ponding of many terraces during rainy periods. Landsliding hazard therefore increases although infinite slope analysis suggested that it remains below critical values if pore-water overpressures are not produced (Haro *et al*., 1992).

CONCLUSIONS

The mineral output from the small catchment of Cal Parisa is clearly dominated by dissolved transport, which is about four times greater than particulate sediment yield. Both the high calcite content of the bedrock, which is dissolved and transported close to saturation levels in streamwaters, and the very low suspended-sediment yield contribute to this behaviour, more typical in very stable forested areas than in those affected by human activities and prone to gully erosion and landsliding (Gregory and Walling, 1973; Slaymaker, 1988).

The strikingly low suspended-sediment yield is the result of practically nil erosion in grassed terraces together with strong sediment conveyance discontinuities that disconnect erosion processes active in scattered degraded areas. This picture is representative of most small catchments within this area. Greater catchments, having badland areas or streams with unstable eroded banks, supply high amounts of sediments (Clotet and Gallart, 1986). This provides a representative example of the inadequacy of the 'average erosion rate' calculated for a large catchment, and the need for studies on sediment sources and conveyance discontinuities.

The method used for mineralogical and chemical analyses provided useful information with the advantage of using common one-litre water samples. Even in this small catchment, the sediment characteristics do not correspond to those of the materials from source areas; the Mn enrichment of transported sediments does not fit the explanations usually proposed, and deserves further research.

From the geomorphological point of view, the low sediment yield does not correspond to low geomorphic activity, nor to a tendency to stability in this catchment. The initial period after abandonment, which has been studied here, is probably indeed the more stable one, because of the growth of permanent vegetation (dense pastures, bushes and pine trees) on the formerly cultivated fields, with the permanence and activity of the old land conservation structures. Terrace failures do not seem to induce a significant environmental deterioration here, but the peakedness of the hydrological response suggests that the spontaneous reorganization of the drainage net can result in major fully erosion of the terraces that occupy the natural water pathways.

This study attempts to contribute to the scientific foundations for rational policies of land conservation in middle mountain areas where terrace structures suffer abandonment. The major role of the man-made drainage

system observed in the Cal Parisa catchment recommends paying attention to these structures, whose degradation is usually less noticed than that of the terraces themselves, but which can provide the more hazardous aspect for land conservation of these abandoned areas.

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